NWC TP 5832

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Advanced Aerodynamic Control Technology Summary Report

by
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Aeromechanics Division
Weapons Development Department

DECEMBER 1975

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R. G. Freeman, III, RAdm., USN . . . . Commander

G. L. Hollingsworth . . . . Technical Director

FOREWORD

This report summarizes the results of a study of the aerodynamic roll characteristics of canard-controlled missiles. A method for predicting induced roll moments, a simplified method of representing aerodynamic coefficients, and an evaluation of canard and tail slots are described. The material contained in this report has been informally presented in FY 1974 Summary Report (NWC TN 4063-244) and FY 1975 Summary Report (NWC TN 4063-248).

The work was performed partly in-house, partly by contract at Nielsen Engineering & Research, Inc., and partly by the Dahlgren Laboratories of the Naval Surface Weapons Center, during the period from July 1973 to June 1975. Funds were provided under Direct Laboratory Funding Task Area Plan No. ZF32344001, Work Unit No. 151931. The manager of the Task Area Plan was D. N. Livingston. This report has been reviewed for technical content by R. E. Smith.

Released by
M. M. ROGERS, *Head*
Systems Development Department
30 December 1975

Under authority of
G. L. HOLLINGSWORTH
Technical Director

NWC Technical Publication 5832

Published by . . . . Technical Information Department
Manuscript 5362/MS 75-200
Collation . . . . Cover, 18 leaves
First printing . . . . 130 unnumbered copies

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 NWC-TP-5832	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Advanced Aerodynamic Control Technology, Summary Report.		5. TYPE OF REPORT & PERIOD COVERED 9 Summary rep[redacted]t, Jul[redacted]73 -to- June [redacted]75,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 R. E. Meeker		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Weapons Center China Lake, Calif. 93555		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ZF32344001, 151931
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Weapons Center China Lake, Calif. 93555		12. REPORT DATE 11 Dec[redacted]75 12 37p. 13. NUMBER OF PAGES 34
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 16 ZF32-344 17 ZF32-344-001		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; 30 December 1975. Other requests for this document must be referred to the Naval Weapons Center.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Canard control
Missiles
Aerodynamics
Roll characteristics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(U) *Advanced Aerodynamic Control Technology Summary Report*, by R. E. Meeker. China Lake, Calif., Naval Weapons Center, December 1975. 34 pp. (NWC TP 5832, publication UNCLASSIFIED.)

(U) The objective of the work described in this report was to develop a better understanding of the aerodynamic roll characteristics of canard controlled missiles. Studies were performed to develop a method of predicting induced roll moments, a method for simplified representation of aerodynamic coefficients in simulations, and to evaluate the use of canard and tail slots. This report summarizes the results obtained.

CONTENTS

NOMENCLATURE

C_l	$\frac{L}{qsd}$,	Roll moment coefficient
C_m	$\frac{M}{qsd}$,	Pitch moment coefficient
C_N	$\frac{N}{qs}$,	Normal force coefficient
C_n	$\frac{n}{qsd}$,	Yaw moment coefficient
C_Y	$\frac{Y}{qs}$,	Yaw force coefficient
d	Body diameter, ft	
L	Roll moment, ft-lb	
M	Pitch moment, ft-lb	
N	Normal force, lb	
n	Yaw moment, ft-lb	
P	Roll rate, rad/sec	
q	Dynamic pressure, lb/ft^2	
s	Body cross-section area, $\frac{\pi d^2}{4}$ ft^2	
V	Velocity, ft/sec	
Y	Yaw force, lb	
α	Angle of attack, deg	
β	Angle of sideslip, deg	
δ_H	Deflection of pitch canards, deg	
δ_V	Deflection of yaw canards, deg	
ϕ	Roll attitude deg $\phi = 0$ when yaw canards are in vertical plane	
ϕ_A, ϕ_R, δ_R	See Figure 12	

INTRODUCTION

The canard-controlled airframe has several features which make it attractive for use in guided missiles. The fact that the seeker, guidance electronics, servo, warhead, and propulsion systems can be located in the above order from front to rear naturally tends to minimize the number of electrical or hydraulic lines that must pass through the warhead and the propulsive unit. Also, since the servo actuator is separated from the area of the propulsive rocket nozzle, the design of each is not compromised by the presence of the other. The canard is also a powerful aerodynamic control, capable of trimming a missile to large angles of attack and producing high levels of maneuverability. In the design of a family of modular weapons, it is expected that these features would assume even greater attractiveness.

But, there are difficulties. The highly maneuverable canard airframe will possess some very nonlinear aerodynamic characteristics, thus complicating the task of modeling for simulations. Also, the canard airframe generally has very large induced roll moments--moments which are also complicated functions of the control deflections, and pitch, yaw, and roll attitudes of the missile. Control of the rolling motion through differential deflection of the canards (as ailerons) is also generally considered impractical--large variation of the roll control power with variation of Mach number, angle of attack, etc., are expected. Thus, the use of the canard-controlled airframe for missiles generally has been restricted to simple missiles with no, or only rate-type, roll control. If the problems associated with the induced roll moment and roll control (attitude) were solved, this type of airframe would see more use, particularly in the case of modular weapons.

The objective of the work described herein is to develop the best possible understanding at this time of the aerodynamics of canard-controlled airframes with particular emphasis on the aerodynamic roll characteristics.

PROGRAM DESCRIPTION

In order to meet the objectives of the program, three separate but related efforts have been pursued. These are:

1. The development of a method to predict the induced roll characteristics of cruciform canard airframes.

2. An investigation of a concept to more simply model the aerodynamic characteristics of canard missiles for simulation purposes.

3. An experimental investigation of promising concepts to alleviate the effects of large induced roll moments of canard missiles.

Each of these program areas are described in more detail, outlining the major results obtained to date. These have also been previously reported informally.[1,2]

PREDICTION METHOD

The development of a method for the prediction of the induced roll characteristics of canard control missile configurations was contracted to Nielsen Engineering & Research, Inc. (NEAR), Mountain View, Calif. The method was to be of an engineering nature, i.e., whatever mixture of theory and empiricisms needed to give fairly rapid results of reasonable accuracy. The method was to be applicable at subsonic and supersonic speeds, at angles of attack up to 20 deg, at any combination of pitch or yaw control deflections up to 20 deg, and at arbitrary roll angles. The contract was conducted in three parts as follows:

Part I was an assessment of the then current state-of-the-art in predicting induced rolling moments to identify important parameters in the problem, to identify serious deficiencies in theoretical methods and available data, and to assess the kind of results that could be obtained.

Part II was to develop and carry out a wind tunnel test to obtain additional data identified as needed in Part I.

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[1] Naval Weapons Center. *Advanced Aerodynamic Control Technology FY 1974 Summary Report*, by R. E. Meeker. China Lake, Calif., NWC, August 1974. (NWC TN 4063-244.)

[2] Naval Weapons Center. *Advanced Aerodynamic Technology FY 75 Summary Progress Report*, by R. E. Meeker. China Lake, Calif., NWC, July 1975. (NWC TN 4063-248.)

Part III was to use the results of Part II to improve on the prediction methods used in Part I. Included was the development of computer programs to permit automatic and rapid computation, and a final report documenting the completed project.

Part I. State-of-the-Art Assessment

A summary of this work was reported[3] and included details of the calculations that are described briefly below.

Calculations were made for the AIM-9L configuration, shown in Figure 1, to compare calculated rolling moments with data for cases where the induced rolling moment was felt to be due principally to canard-tail interference. The cases selected were data for the complete missile at angle of attack and at zero bank with the yaw canards deflected. The results are shown in Figures 2 and 3 for Mach 0.4 and 2.5, respectively.

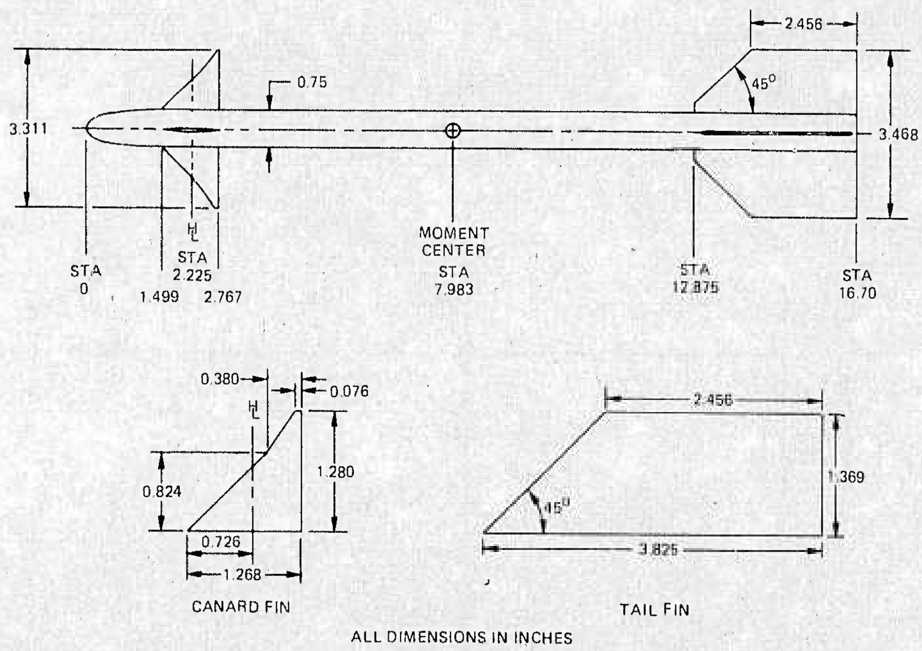

FIGURE 1. AIM-9L Sidewinder Wind Tunnel Model.

[3] Nielsen Engineering & Research, Inc. *A Study of Indueed Rolling Moments for Cruciform-Winged Missiles*, by J. N. Nielsen, Selden B. Spangler, and Michael J. Hemsch. Mountain View, Calif., NEAR, December 1973. (NEAR TR 61.)

The body-canard and body-tail data indicate that the effects of panel-panel and body vortex-tail interference on rolling moment are negligible for the case of Figure 2 so that almost all of the moment illustrated therein should be due to canard-tail effects. The figure shows results for δ_V = 20 deg with δ_H = 0 and 10 deg. The data show a consistent pattern both with angle of attack and δ_H deflection. The theory predicts the same qualitative behavior, but the magnitudes of the peak rolling moments are approximately half those indicated by the data. The reason for the discrepancy is not known, but several possible causes are subsequently discussed. Sensitivity tests were made changing the strengths of the vortices by 10%, and these indicated small changes in induced rolling moments. Also, calculations were made assuming the vortices left the canard panels and moved aft under the influence only of the free-stream velocity. No significant differences in induced rolling moment were observed between this case and that based on the previous vortex trajectory method.

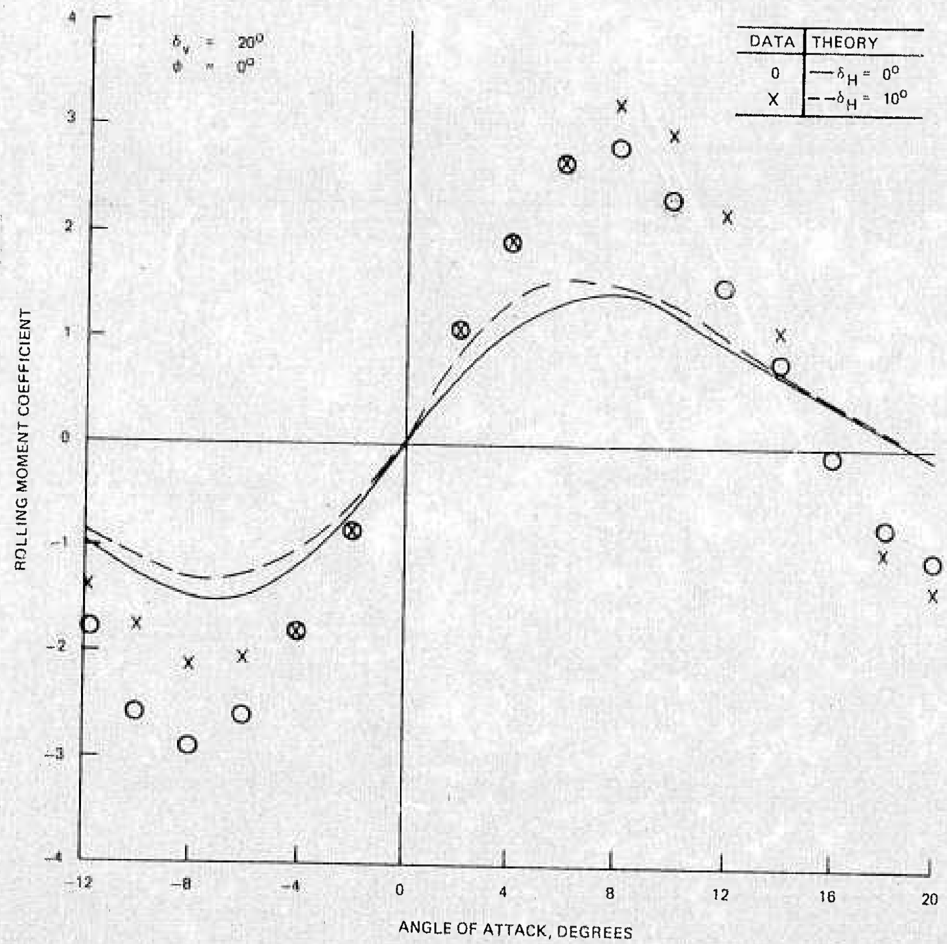

FIGURE 2. Predicted and Measured Rolling Moment on AIM-9L at M = 0.4.

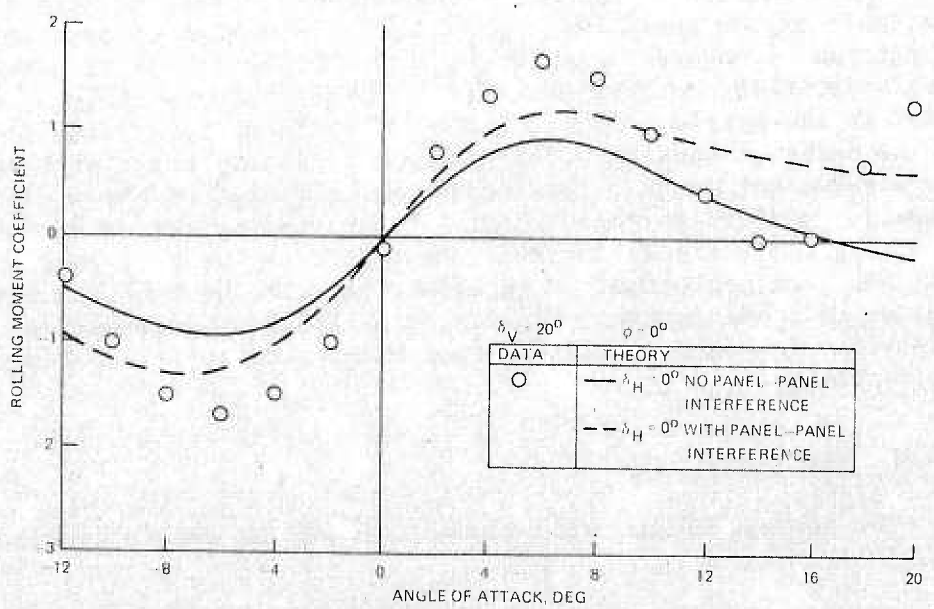

FIGURE 3. Predicted and Measured Rolling Moment on AIM-9L at M = 2.5.

Figure 3 shows similar results for Mach 2.5. Again, the theory underpredicts the data, although by a lesser degree than for the lower Mach numbers. For this Mach number, the canard-body data indicate a small panel-panel interference, which is shown added to the canard-tail predicted rolling moment in Figure 2. The addition of the measured panel-panel interference to the canard-tail theory does not improve the agreement although, by comparison of the data in Figures 2 and 3, there does appear to be some effect which adds positive roll at high angles of attack at the higher Mach number.

On the basis of the calculations and comparisons made, it was felt that the methods used were describing the basic physical phenomena properly. However, there are several limitations of the preliminary theory that need further work in order to properly handle the flow conditions of interest, and these may be responsible for the lack of quantitative agreement between existing theory and experiment. In particular, the methods used to obtain the relationship between span-loading and span-circulation distribution are based on linear theory and have not been verified by experiment.

Another possible source of rolling moments not considered in the calculation is afterbody vortices. If body-separation vortices are formed downstream of the canards, it is probable that there will be some interaction between the canard and body vortices, so that the body vortices will become asymmetric and induce rolling moment for

zero bank angle. The body vortices will also affect the positions of the canard vortices. At the present time, there is neither information available on the qualitative nature of reformation of body vortices downstream of canard surfaces, nor is there an interaction model between body separation and free vortices. Several other sources of uncertainty exist in the method. First, the vortex-induced flow field is calculated on the basis of Rankine vortices. Better models exist such as those for a turbulent vortex. However, some knowledge of the vortex core sizes is required to apply them. Second, the effect of the empennage in moving the vortices laterally or vertically as they pass over the tail has been neglected. This effect can also be included but at the expense of complication. Finally, the method of determining the vortex trajectory is based on slender-body theory and needs experimental verification.

Part II. Wind Tunnel Test

The purpose of the wind tunnel test was to obtain systematic data on:

1. Panel-panel interference effects for high- and low-aspect ratio canard and tail surfaces.

2. Body vortex interference on low-aspect ratio tail panels.

3. Canard vortex-tail interference.

4. Interaction between body and canard vortices.

5. Vortex trajectories.

The model configuration tested is shown in Figure 4. The normal force, root bending moment, and panel hinge moment were measured for each canard panel and each tail panel separately, as well as six component main balance forces and moments. In addition, vapor screen movies were obtained at selected test conditions. The tests were performed at Mach 0.8, 1.30, and 1.75, at angles of attack from 0 to 24 deg, and canard deflections of 0 and 15 deg. The tests included body build-ups, i.e., body, body-canard, body-tail, and body-canard-tail configurations, and roll angles of 0, 10, 20, 30 and 45 deg. A detailed test report, including a small amount of summary data, is presented in NEAR TR 72.[4] A complete set of plotted data, data tapes, and vapor screen movies are available, and a test report will be published by National

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[4] Nielsen Engineering & Research, Inc. *Test Report for Canard Missile Tests in Ames 6- by 6-Foot Supersonic Wind Tunnel*, by M. J. Hemsch and J. N. Nielsen. Mountain View, Calif., NEAR, August 1974. (NEAR TR 72.)

Aeronautics and Space Administration (NASA). NEAR, Inc., analyzed the force test data, as needed, and the results, for correlation with predictions, are included in NEAR TR 75[5] and TR 79.[6] NEAR also analyzed a selected portion of the vapor screen pictures and reported the results in TR 81.[7]

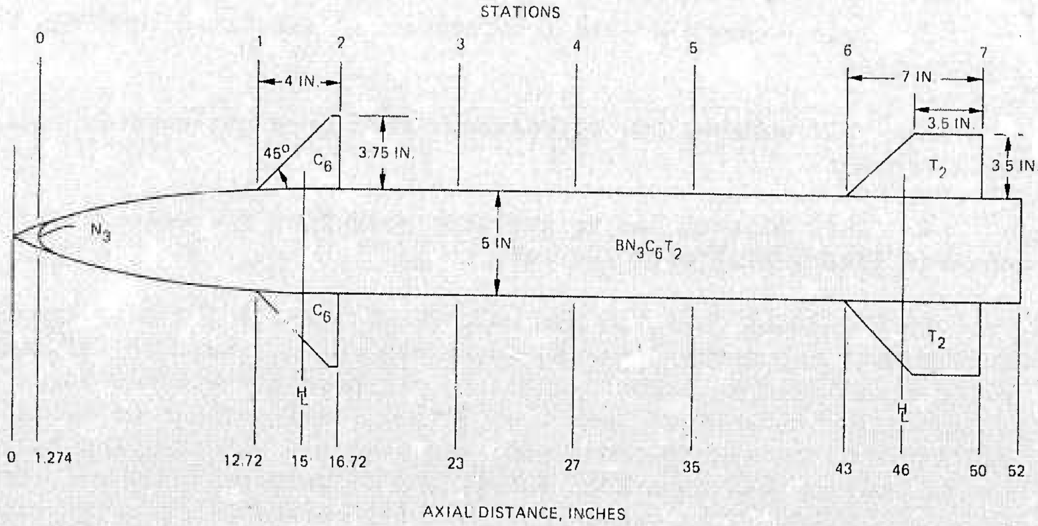

FIGURE 4. Dimensions and Stations of Canard Cruciform Missile Used in Test Program.

Part III. Development of Prediction Methods and Computer Programs

The method for estimating induced roll characteristics was completed by NEAR, Inc. Development of the method and correlations with the wind tunnel data of Part II are given in reports referenced in Footnotes 5 and 6. The summary report[8] presents the final choice of calculative procedures, documents the computer programs used, and illustrates the use of the method.

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[5] Nielsen Engineering & Research, Inc. *The Induced Rolling Moments of Cruciform Wing-Body Combinations as Influenced by Panel-Panel Interference*, by J. N. Nielsen, M. J. Hemsch, and M.F.E. Dillenius. Mountain View, Calif., NEAR, November 1974. (NEAR TR 75.)

[6] Nielsen Engineering & Research, Inc. *Further Studies of the Induced Rolling Moments of Canard-Cruciform Missiles as Influenced by Canard and Body Vortices*, by J. N. Nielsen, M. J. Hemsch, and M.F.E. Dillenius. Mountain View, Calif., NEAR, January 1975. (NEAR TR 79.)

[7] Nielsen Engineering & Research, Inc. *Reduced Vapor Screen Data From Canard Missile Tests in Ames 6- by 6-Foot Supersonic Wind Tunnel*, by M. J. Hemsch. Mountain View, Calif., NEAR, February 1975. (NEAR TR 81.)

[8] Naval Weapons Center. *Methods for Calculating Induced Rolling Moments for Cruciform Canard Missiles at Angles of Attack Up To 20 Deg*, by M. J. Hemsch, J. N. Nielsen, and M.F.E. Dillenius, Nielsen Engineering & Research, Inc. China Lake, Calif., NWC, May 1975. (NWC TP 5761.)

The method considers the following sources of induced roll moment:

1. Roll moments of the cruciform canard and tail panels, including the effects of wing-body interference, wing-wing interference, and coupling effects between the angle of attack and yaw canard deflection and the angle of sideslip and pitch canard deflection.

2. Roll moments due to interaction of shed nose vortices with the canards.

3. Roll moments due to vortices shed from the canards interacting with the tail.

4. Roll moments due to vortices shed from the body aft of the canards interacting with the tail.

It was found that, in general, items 3 and 4 dominate the induced roll moment and items 1 and 2 can be neglected. However, although the effects included in items 1 and 2 do not directly produce large roll moments, the effects of item 1 do have a strong effect on the lift carried by each canard panel and, thus, on the strength and position of the vortex shed from that panel, and so must be included. Exceptions to these generalities probably exist; for example, a configuration with a long nose, forward of the canards, might produce nose vortices strong enough to produce significant roll moments on the canards.

The method of calculating the effects listed above are, in general, based upon the slender body approximation of linear flow theory. Modifications are introduced where needed and where possible to account for nonslender and nonlinear effects.

To illustrate the type of approximations used, consider the problem of calculating the lift of each individual canard panel (neglecting nose vortices). In order to account for the various interference effects (wing-body, wing-wing) and coupling effects ($\alpha\beta$, $\alpha\delta_V$ and $\beta\delta_H$), interference factors, based on lift ratios, are introduced for each effect. These interference factors are calculated from slender body theory subsonically, and either from slender body theory or by use of a linear, finite element, cruciform wing-body computer program supersonically. The concept of an "equivalent angle of attack" is then introduced for each canard panel, defined as the angle of attack of an isolated panel which will produce the same normal force as the panel (in the presence of the body and other panels and with α, β, and δ) being considered. The equivalent angle of attack is computed from the geometric angle of attack, sideslip and control deflections, and the interference factors. Note that, particularly for the canards, the equivalent angles of attack can be quite large, over 40 degrees, and well into the nonlinear

region of normal force. The normal force for the panel is then obtained from a curve of normal force versus angle of attack at the equivalent angle of attack. If this curve is nonlinear, then the effect of nonlinear normal force is included. Methods for computing the normal force curve for isolated wings to high angles of attack are not presented by NEAR; however, several methods of obtaining the normal force curve are illustrated. The validity of this method of computing the panel force contributions to the induced roll moments remains to be shown by comparison with data. However, it was shown by NEAR, in a few cases, that a reverse application of the concept to body-canard data taken at various Mach numbers and combinations of angle of attack, roll angle and canard deflection did correlate the panel normal forces very well.

Four computer programs are supplied by NEAR to carry out the following computations:

1. A cruciform, wing-body lifting surface finite element computation at supersonic speeds. This program is based on linear theory and may be used in the prediction method for calculating the various interference factors needed to obtain the equivalent angles of attack at supersonic speeds. This program may also be used to compute the rolling moments on the tail due to body and canard vortices as well as the interference effects, but the results are strictly linear and do not include the nonlinear panel normal force effects. This program is the most time consuming to use, and requires a large amount of input and setup as well as actual computing time.

2. A vortex trajectory computing program. This program computes the trajectories of free vortices (as from the canards) in the presence of a circular body and up to two bound vortices whose strength, as well as position is varying. Bound vortex strength is computed from crossflow drag momentum exchange analogy. The program can also be used to estimate trajectories of multiple shed body vortices, provided sufficient information is known to specify where the vortices become free and new bound vortices start. Starting positions and strengths of all vortices must be input.

3. A program to compute vortex trajectories past lifting surfaces. The computation is based on slender body theory and is used only to compute nose vortex trajectories past the canards. So far this program has not been used at NWC.

4. A program to compute the effect of free vortices on lifting surfaces. This program actually computes the equivalent angle of attack due to the vortices from which the normal force and rolling moment are obtained as explained earlier. The computation is based on slender body theory and uses the reverse flow analogy.

Typical computer run times on the NWC UNIVAC 1110 are as follows:

	Run time, minute
Cruciform Lift Surface Program	1.0
Vortex Trajectory Program	0.05
Vortex Induced Roll Moment Program	0.05
Vortex Trajectory Past Lift Surface	0.1

At present, these programs are separate and not linked together for automated computation. The user must transfer data output from one program to input to the next. In addition, a substantial amount of hand computation remains for the user. While much of this hand manipulation could be automated, it has not been done.

In the final analysis, the determination of the value of the method will depend on comparisons with data. At the present time, a very limited number of such comparisons have been made. Figure 5 shows a comparison of prediction with measurement for the AIM-9L configuration shown in Figure 1. Figures 6 through 9 show similar comparisons for the MICOM model shown in Figure 4. Figure 11 shows a comparison for the configuration shown in Figure 10. This data was taken from the report referenced in Footnote 9. As is apparent from these checks, both good and poor predictions have been made, and the reasons for poor correlations are not yet evident.

SIMPLIFIED MODELING OF AERODYNAMICS

One of the stumbling blocks to accurate six-degree-of-freedom simulations of missile motions is the increase in amount and complexity of the aerodynamic information that must be input to the computer. This increase, due only to the effects of varying roll attitudes and roll rates on the aerodynamics, can amount to a ten-fold increase when using conventional axes systems to represent the data (i.e., body axes or nonrolling body axes, etc.).

[9] National Aeronautics and Space Administration. *Aerodynamic Characteristics at Mach 0.60 to 4.63 of Two Cruciform Missile Models, One Having Trapezoidal Wings With Canard Controls and the Other Having Delta Wings With Tail Controls*, by W. A. Corlett and D. T. Howell. Langley Research Center, Hampton, Va., July 1973. (TMX-2780.)

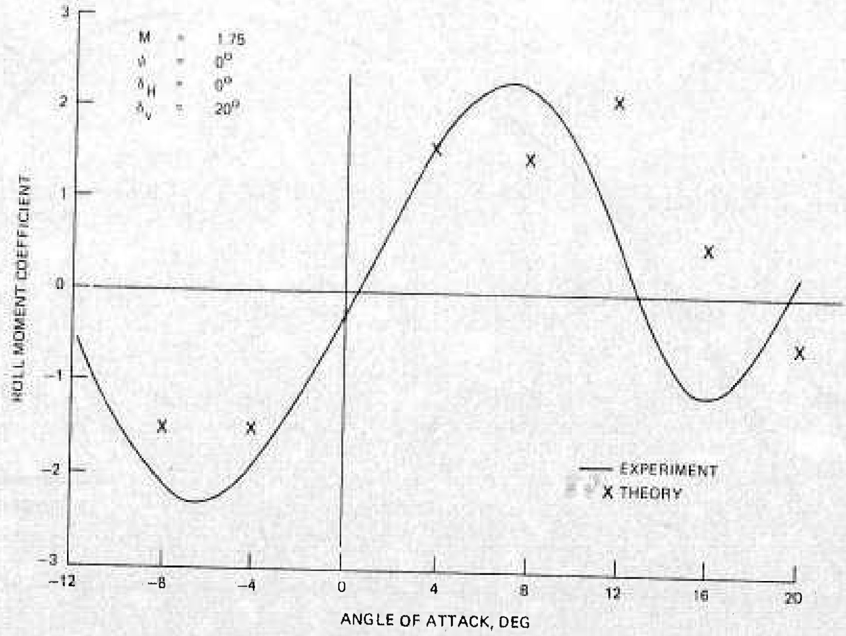


FIGURE 5. Comparison of Experiment and Theory for Configuration of Figure 1.

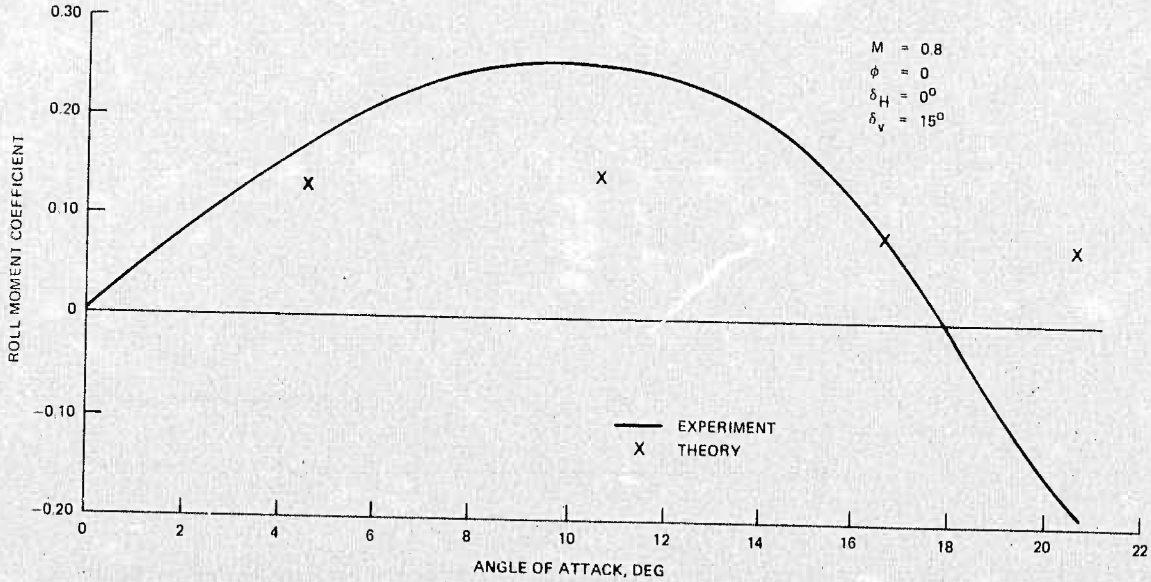


FIGURE 6. Comparison of Experiment and Theory for Configuration of Figure 4.

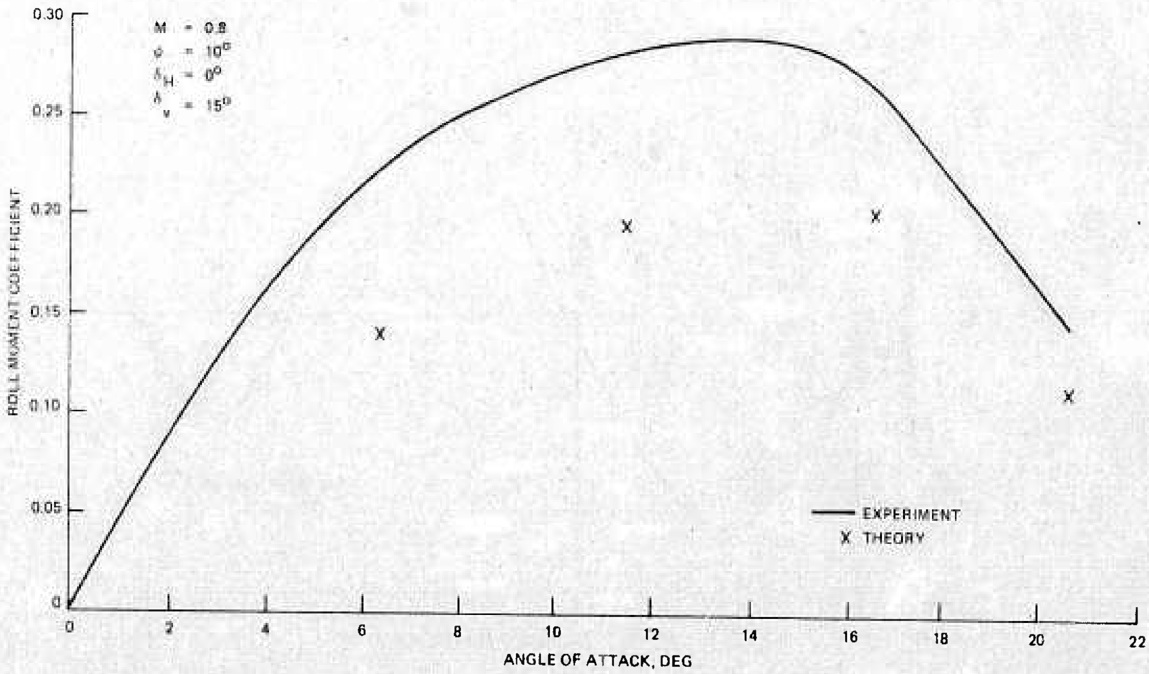


FIGURE 7. Comparison of Experiment and Theory for Configuration of Figure 4.

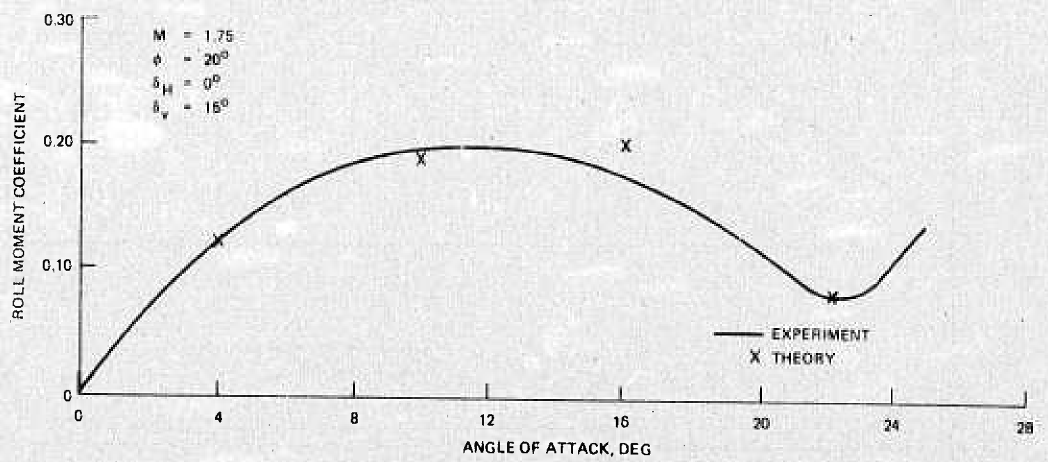


FIGURE 8. Comparison of Experiment and Theory for Configuration of Figure 4.

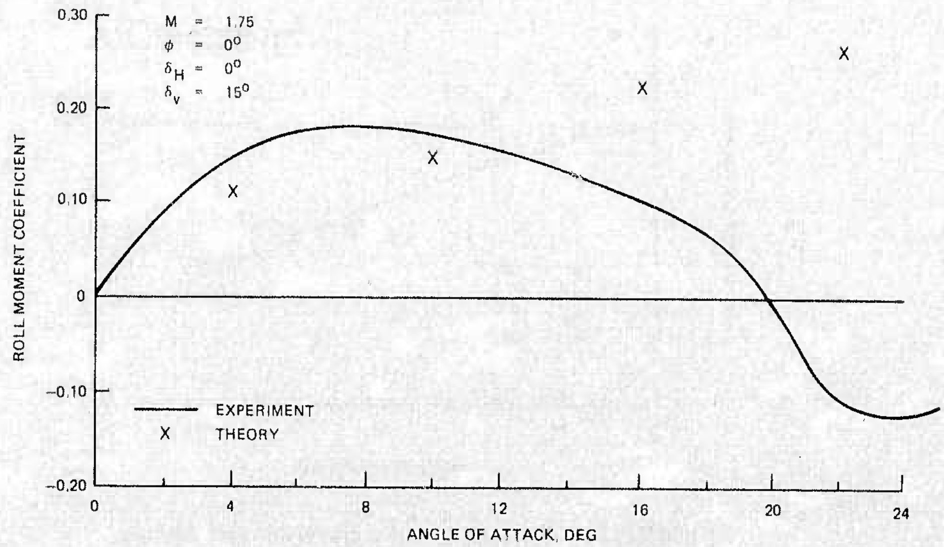


FIGURE 9. Comparison of Experiment and Theory for Configuration of Figure 4.

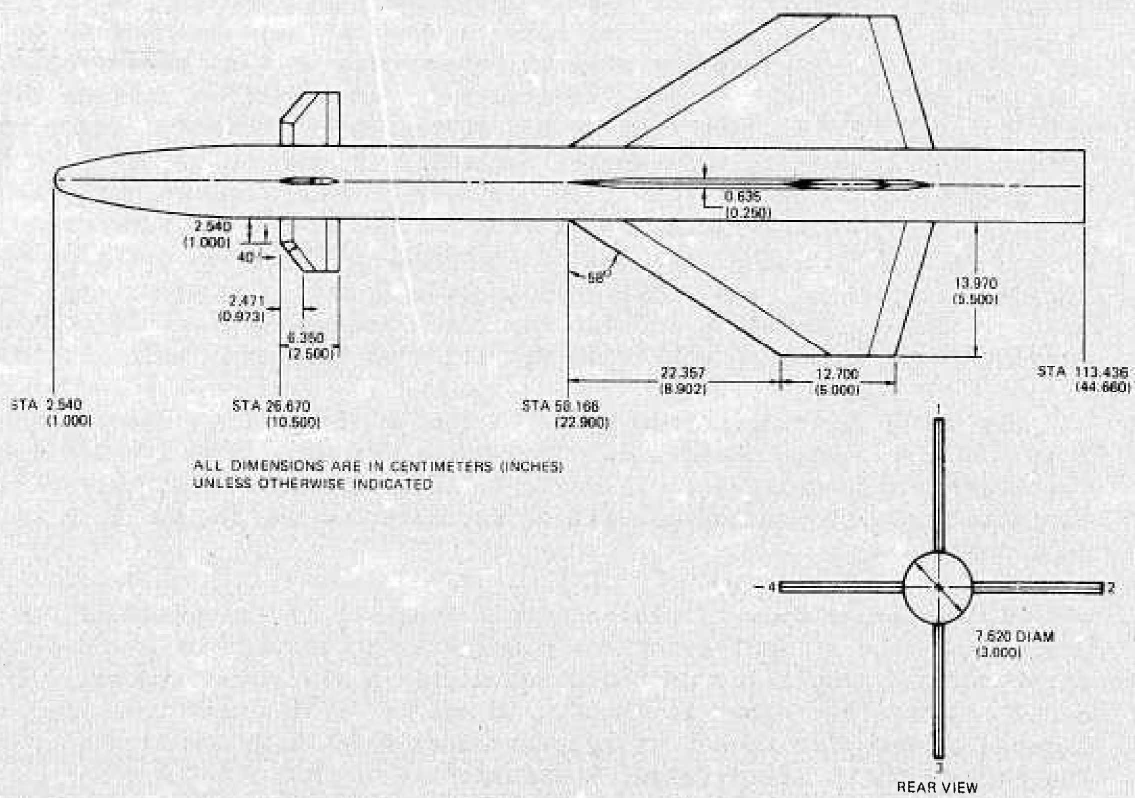


FIGURE 10. Missile Configuration.

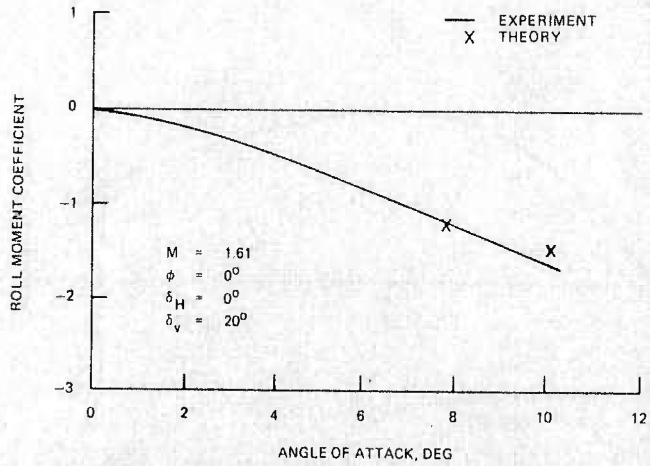


FIGURE 11. Comparison of Experiment and Theory for Configuration of Figure 10.

The objective of this part of the program is to investigate the utility of a proposed way of representing the pitch and yaw control deflections, and their resulting effects upon the aerodynamics of a canard missile. This system will be referred to as the "phase angle axis system" or PAAS. Figure 12 illustrates the idea and defines the various quantities. Note that α_T and ϕ_A represent the total angle of attack and aerodynamic roll angle, respectively, as usually defined for the aeroballistic axes system. The total resultant control deflection δ_R and control roll orientation ϕ_R were defined to be analogous to α_T and ϕ_A. In the PAAS, the set of independent variables defining the aerodynamic attitude and control deflection is composed of α_T, ϕ_A, δ_R, and ϕ_R. The values of δ_H and δ_V, the pitch and yaw control deflection, respectively, will then vary with variation of the model roll attitude.

By using these definitions of the control deflection, it is found that the aerodynamic coefficients are much less sensitive functions of the missile roll attitude. It would be most desirable that the coefficients would become independent of ϕ_A, but this may be too much to hope for.

Before proceeding to evaluate this concept, it was necessary to devise a method of deflecting the canards as a function of the roll attitude in a simple way suitable for use in a wind tunnel model. The means selected are shown in Figures 13 and 14. The inner body is mounted to the wind tunnel sting; the outer model body is mounted to the inner body on low friction bearings.

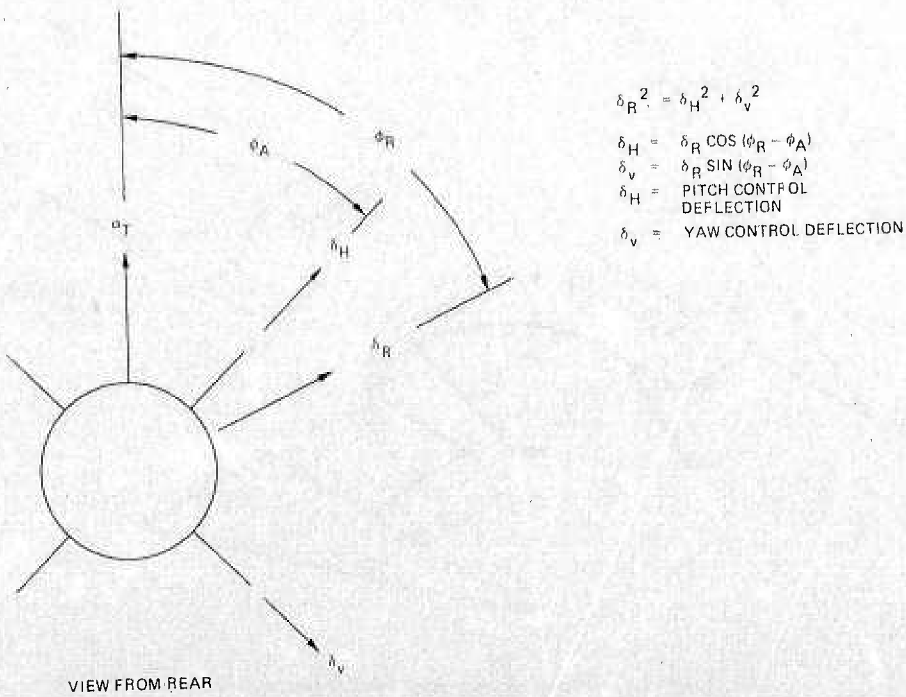


FIGURE 12. Phase Angle Axis System.

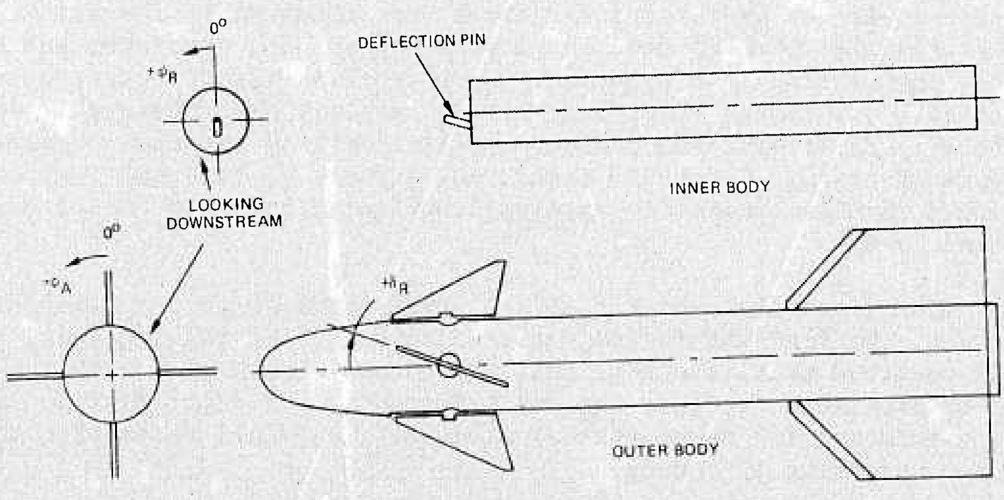


FIGURE 13. Configuration Definition Phase Angle Axis Model.

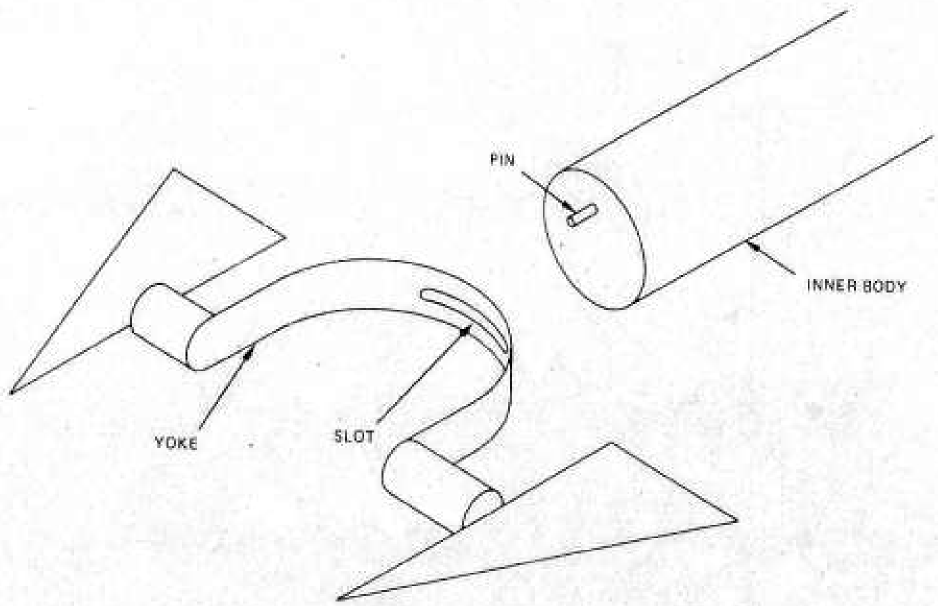


FIGURE 14. Phase Angle Axis Model Canard Detector Details.

Opposing pairs of canards are mounted in bearings in the outer body and are connected to each other by a yoke. A pin in the end of the inner body engages a slot in each yoke. The magnitude of δ_R is set by the amount the pin is offset from the center of rotation. The phase angle ϕ_R is set by rolling the inner body relative to the sting. It was attempted to keep friction low by use of ball bearings, and to keep the pin small in diameter. Some friction was of course present; its effects, though felt to be small, have not been thoroughly evaluated. The effects of friction would be present only in the case of free rolling types of tests. In static tests, the effects of friction would be zero. Figure 15 illustrates the external configuration of the model used for these tests.

The first test was run at low speeds (100 ft/sec) in the NWC wind tunnel. No instrumentation was used in this free rolling test, but it was observed that zero roll rate was obtained only when either α_T or δ_R or both were zero, or when ϕ_R was zero or 180 deg. Maximum roll rate occurred for ϕ_R at approximately 90 deg. Roll rates also increased with increasing α_T and δ_R.

The second series of tests was sponsored by the Air Force Armament Laboratory (DCJA) at Eglin Air Force Base, Fla., and conducted in tunnel 1T at Arnold Engineering Development Center (AEDC), Tullahoma, Tenn. These tests covered Mach numbers of 0.7, 1.15 and 1.4, angles of attack from -6 to +12 deg, δ_R of 0, 10 and 20 deg, aerodynamic roll angles

from 0 to 90 deg, and phase angles from 0 to 210 deg. Five components of static force and moment were measured (excluding axial force). Free rolling tests were also conducted at Mach 0.7 and 1.15. Model spin rates became excessive at Mach 1.4. Static force data, taken from the study referenced in Footnote 10, are shown in Figures 16 through 20. Figure 21 shows the rolling moment for a case where the pitch and yaw canard deflections were fixed. It is evident by comparing Figures 20 and 21 that, while the coefficients are not completely independent of the model roll attitude, the dependence on roll attitude is greatly reduced.

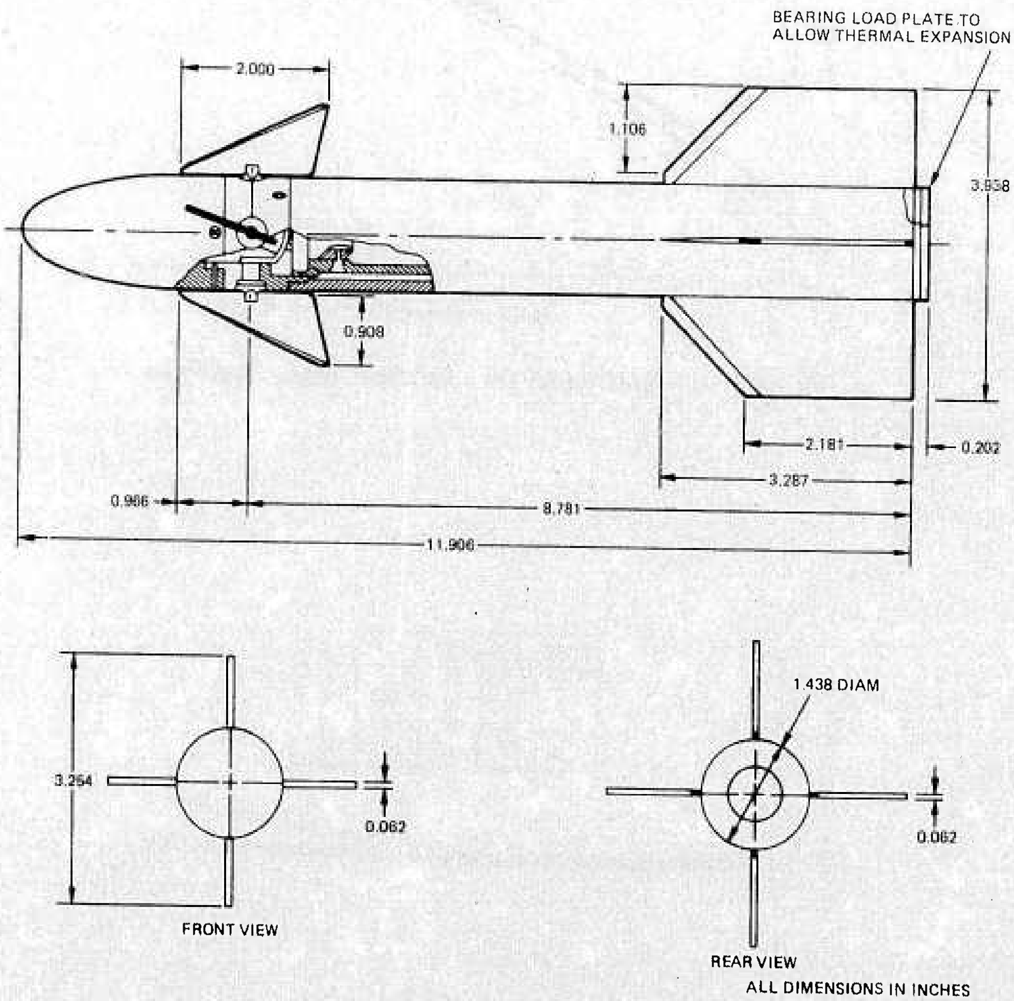


FIGURE 15. Model Details, Phase Angle Axis Model.

[10] Air Research Organization, Inc. *Canard Control Study of the Induced Roll Model at Mach Numbers 0.7, 1.15, and 1.4*, by R. A. Paulk. ARO, February 1974. (AEDC-TR-74-3, AFATL-TR-74-2.)

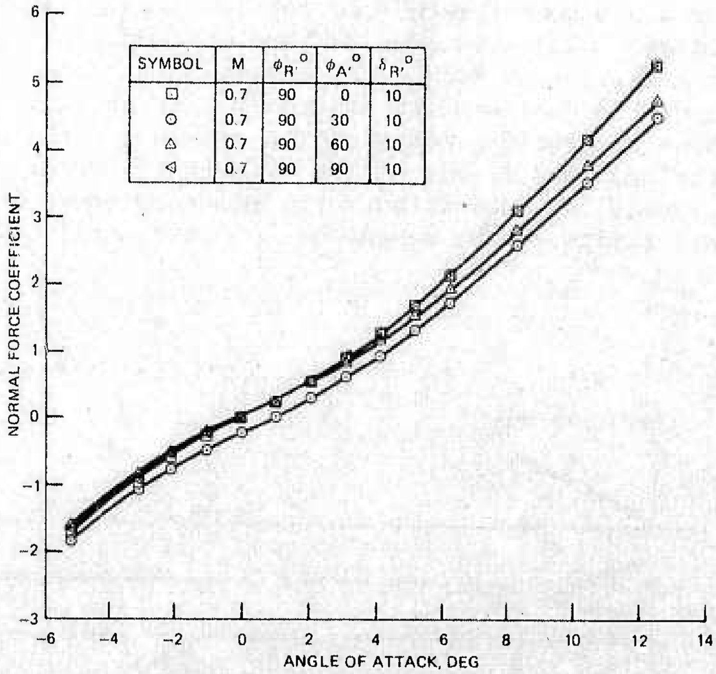


FIGURE 16. Wind Tunnel Data for Phase Angle Axis Model.

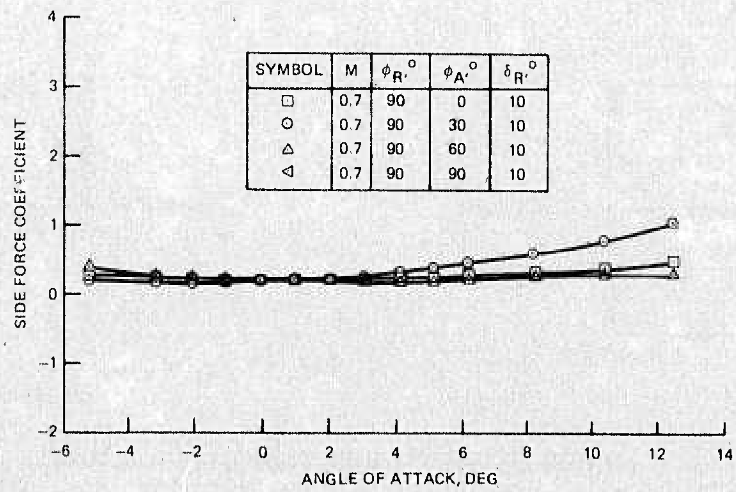


FIGURE 17. Wind Tunnel Data for Phase Angle Axis Model.

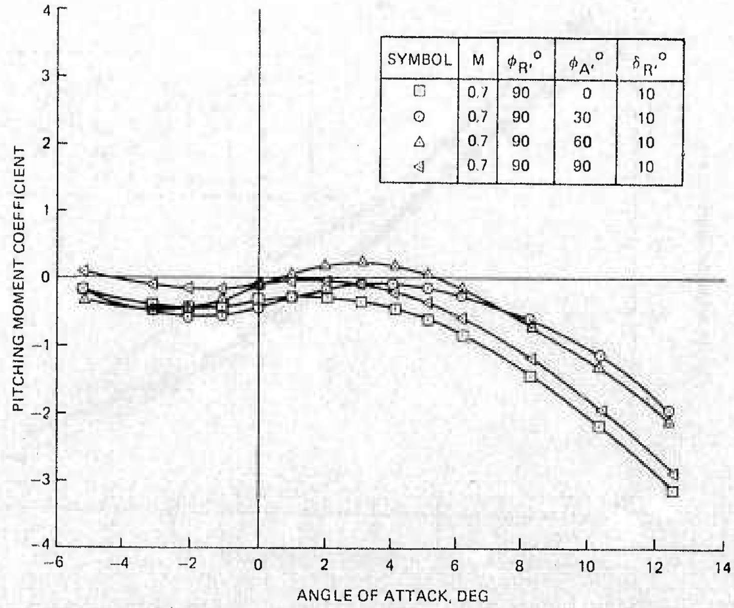


FIGURE 18. Wind Tunnel Data for Phase Angle Axis Model.

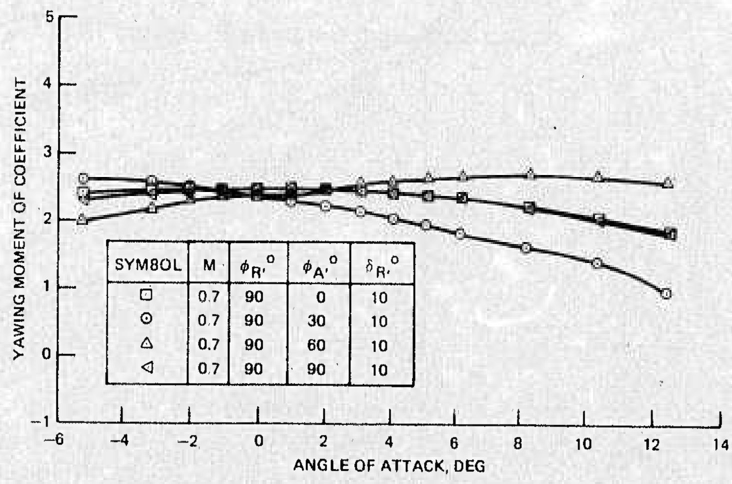
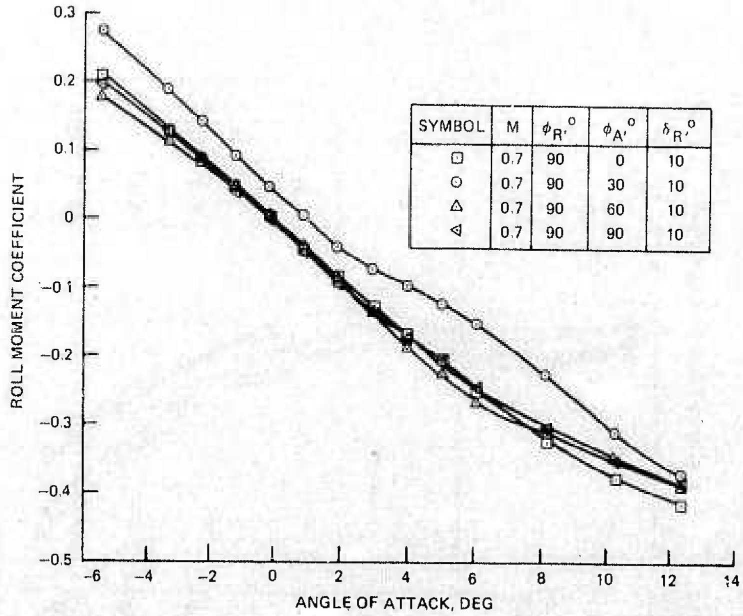
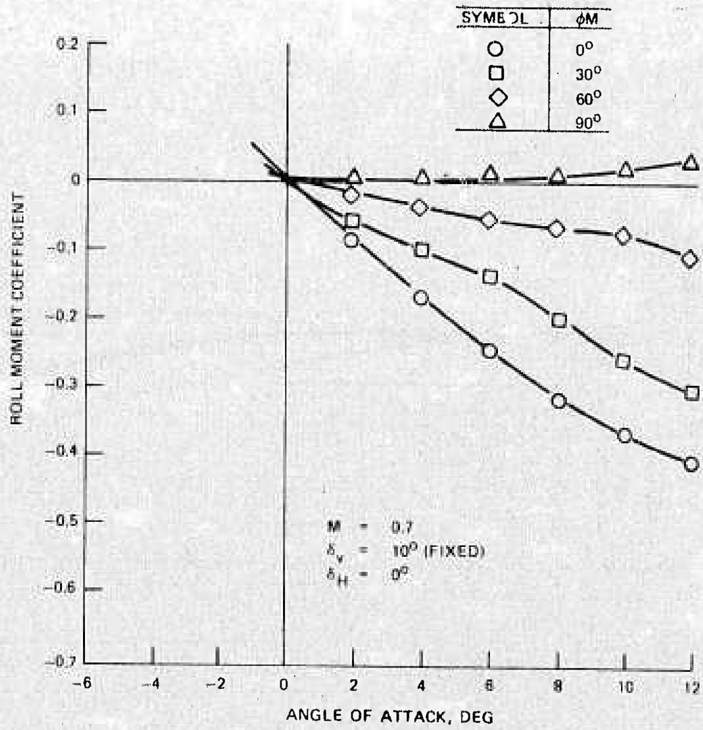


FIGURE 19. Wind Tunnel Data for Phase Angle Axis Model.



SYMBOL	M	ϕ_R, °	ϕ_A, °	δ_R, °
⊡	0.7	90	0	10
○	0.7	90	30	10
△	0.7	90	60	10
◁	0.7	90	90	10

FIGURE 20. Wind Tunnel Data for Phase Angle Axis Model.



SYMBOL	ϕM
○	0°
□	30°
◇	60°
△	90°

FIGURE 21. Wind Tunnel Data for Phase Angle Axis Model.

This encouraging result led to an attempt to convert Sidewinder AIM-9L data, available in the conventional fixed control deflection system, into the PAAS. Many relatively minor corrections had to be made to the AIM-9L data before conversion. These corrections have been made and a computer routine developed to automatically compute the PAAS equivalent coefficients. A limited amount of the data has been converted for comparison purposes. The results for one set of conditions are shown in Figures 22 through 27. Also shown in these figures are similar data in the conventional, fixed canard, notation for comparison. As is evident, once again, the PAAS notation does reduce the dependence of the pitch, yaw, and roll moment coefficients on the missile roll attitude.

EVALUATION OF CONCEPTS FOR ALLEVIATING INDUCED ROLL MOMENTS OR PROVIDING ROLL CONTROL

During the early formulation of this program, a number of ideas existed for either reducing the large induced roll moments associated with canard-controlled airframes or for providing some measure of roll control--either increased roll damping or roll attitude control. These ideas were:

1. Free to spin tail and similar ideas
2. Ring tail
3. Slotted canard and/or tail
4. Differential canards
5. Choice of canard and tail geometry
6. Rollerons and rolleron derivatives
7. Phase angle control.

It was hoped that the utility of several of the more promising or previously least investigated ideas could be evaluated; prudent fiscal policy dictated that only one could be handled.

It was decided that the slotted fin concept showed the greatest potential for alleviating induced rolling moment without complicated mechanical changes to the airframe. Peter Daniels of the Naval Weapons Laboratory, Dalgren, Va., was contracted to perform this study. It was originally planned to conduct wind tunnel tests of a free spinning model identical in principle and external configuration to that described in Part 2 (p. 8), except for the introduction of slots in the canards and tails. This was done and reported.[11]

[11] Naval Surface Weapons Center. *The Effect of Fin Slots on the Free Rolling Characteristics of a Missile Configuration With Commutating Canard Controls and a Cruciform Stabilizer*, by Peter Daniels. Dahlgren, Va., NSWC. (Report in process.)

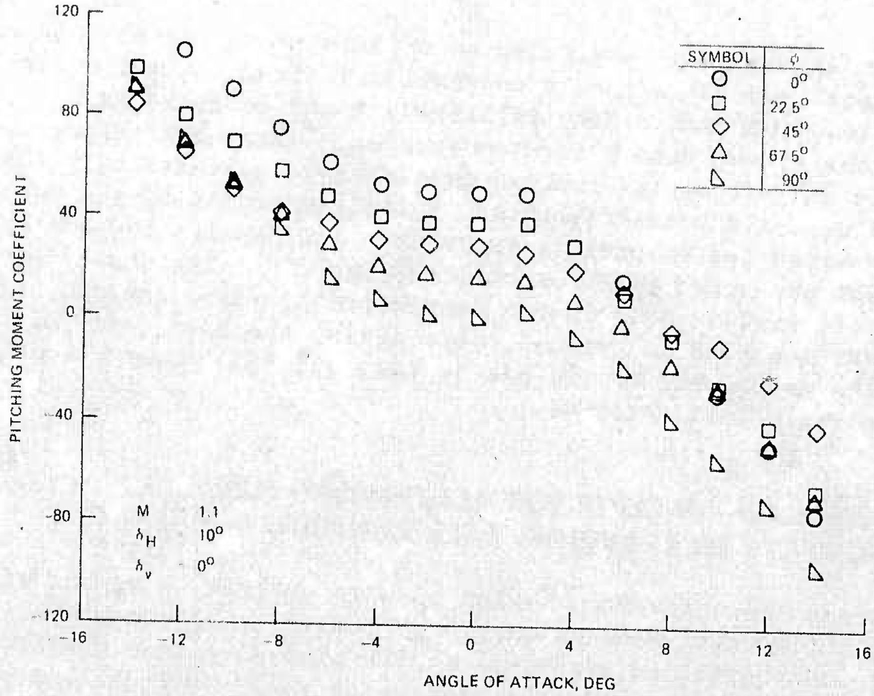


FIGURE 22. AIM-9L Wind Tunnel Data, Conventional Axes.

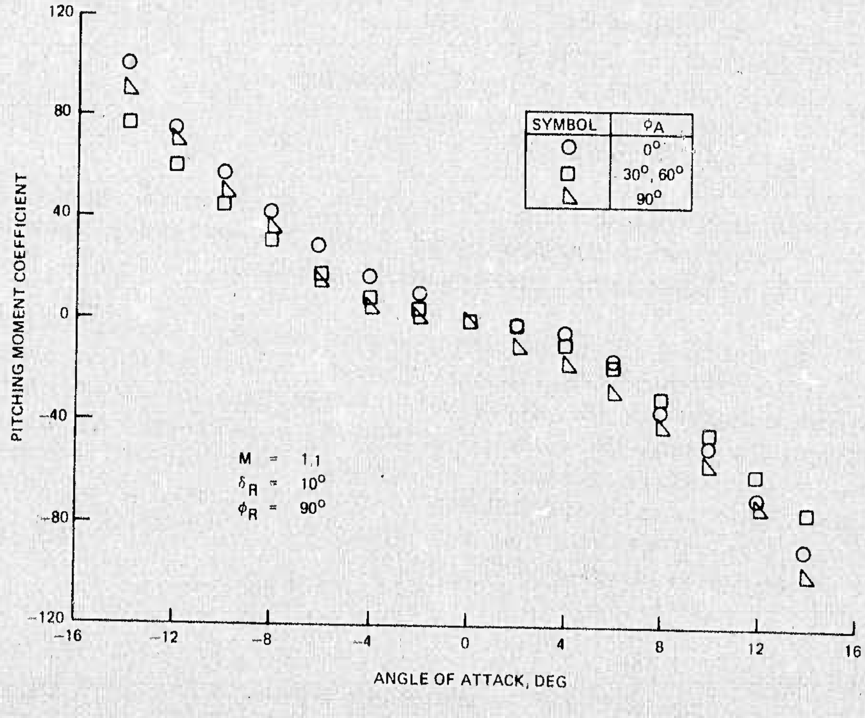


FIGURE 23. AIM-9L Wind Tunnel Data, PAAS.

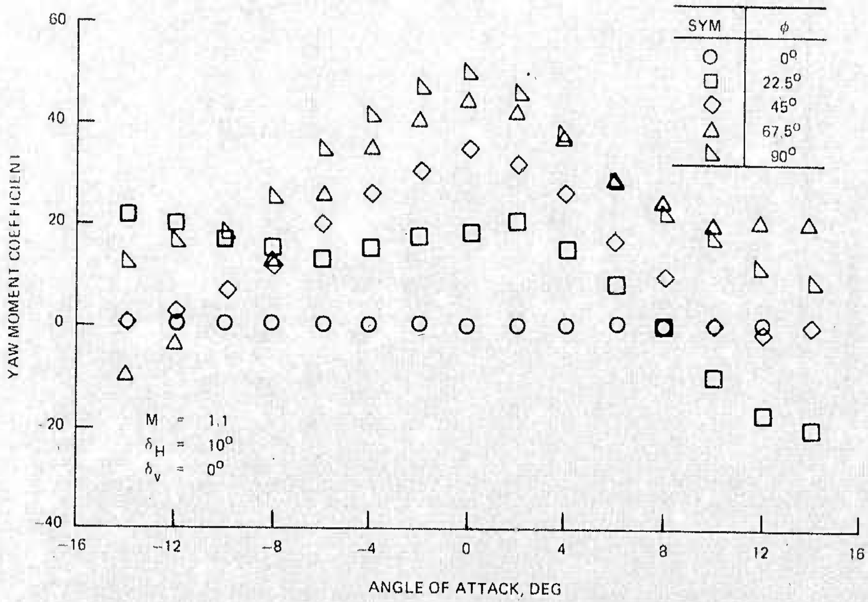


FIGURE 24. Conventional Axes.

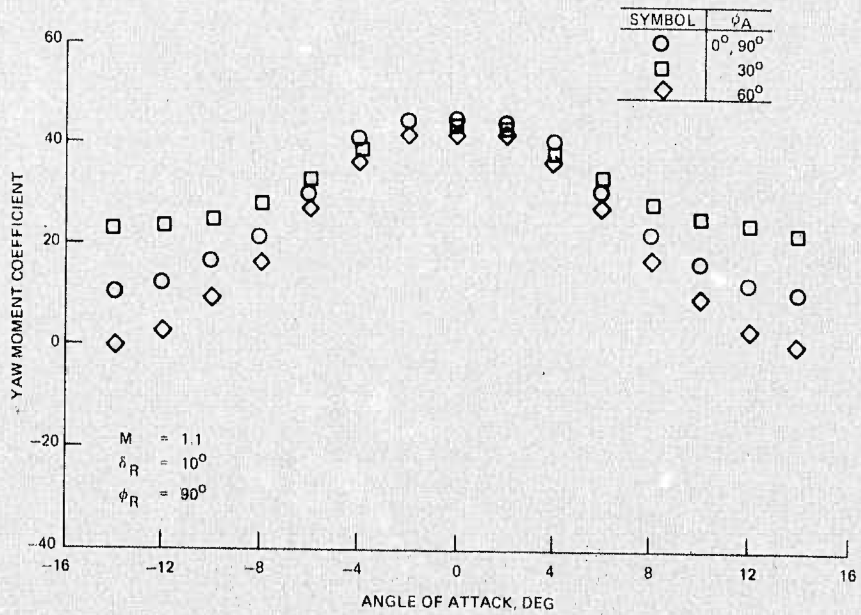


FIGURE 25. AIM-9L Wind Tunnel Data, PAAS.

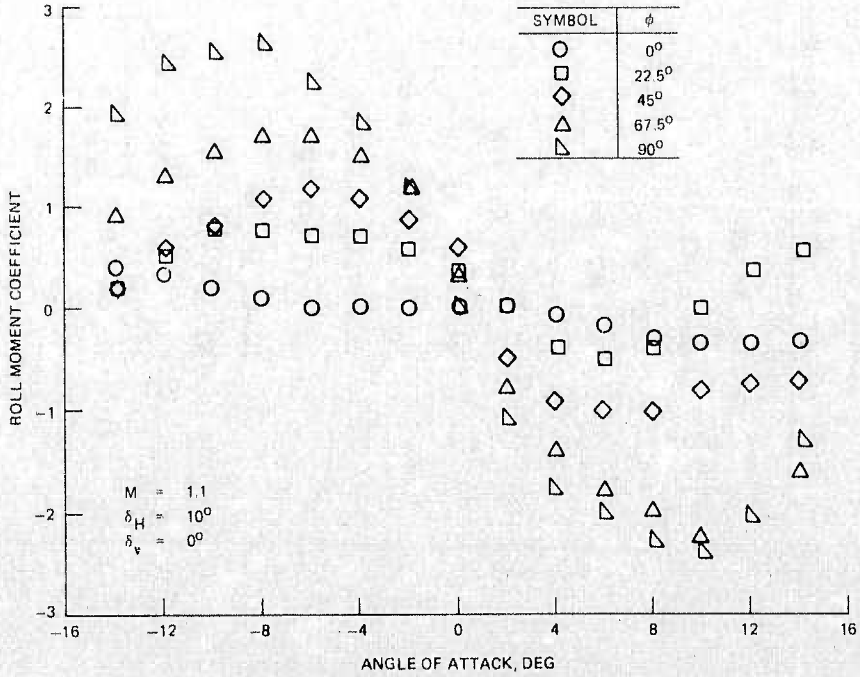


FIGURE 26. AIM-9L Wind Tunnel Data, Conventional Axes.

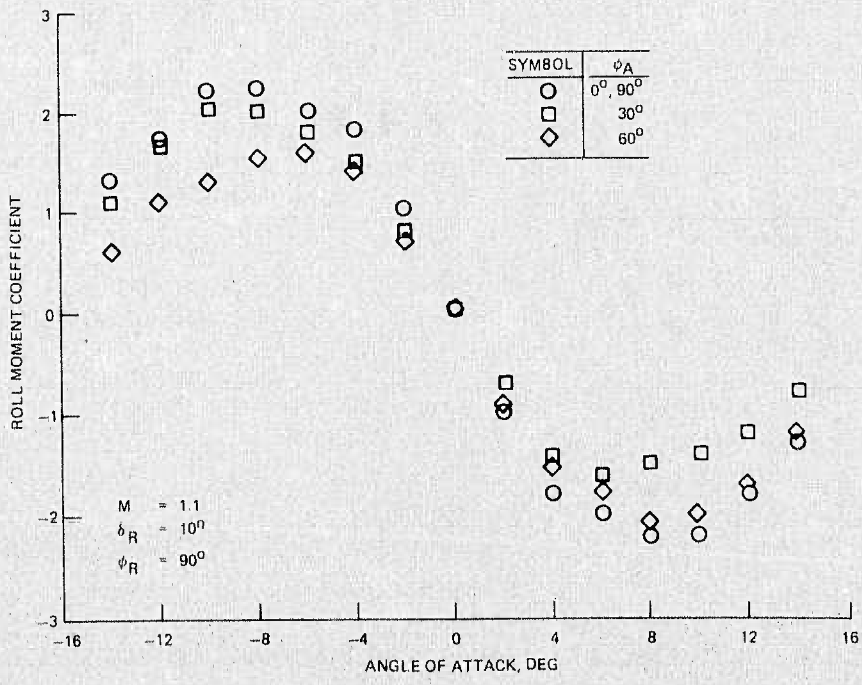


FIGURE 27. AIM-9L Wind Tunnel Data, PAAS.

Figure 28 is a sketch of the wind tunnel model configuration. The external geometry is identical to the model tested at AEDC, although the internal details are somewhat different since the model was intended for tests at speeds of up to 200 ft/sec only. These tests were conducted in the 28- x 40-inch low-speed wind tunnel at Edgewood Arsenal. In the actual tests, the model was deflected in the yaw plane and the cited references show results oriented to the case of a missile in yawed flight. For the sake of continuity, the author has translated these results to the pitch plane for this report. The angle of attack tested was from 0 to ±60 deg. Control deflection δ_R was 0 and 20 deg. The phase angle ϕ_R was tested at 0 and 90 deg, corresponding to minimum and maximum induced roll rates. Figures 29 and 30 illustrate the results of no slots in the canard or tail. The results, out to angle of attack of 20 deg, agree with previously presented data. The results (large spin rates) from 20 to 60 deg is consistent with previous observations of fin stabilized unguided missiles. Figure 31 shows the effect of a 42% slot in the tail. Although the large angle of attack spin rates are reduced greatly, the behavior between ±20 deg is not greatly affected. Essentially the same result was obtained for all sizes of canard slots, tail slots, and combinations tested. Thus, for a canard-body-tail configuration, it was concluded that canard and/or tail slots would not produce much effect on the induced roll behavior within the angle of attack range of interest.

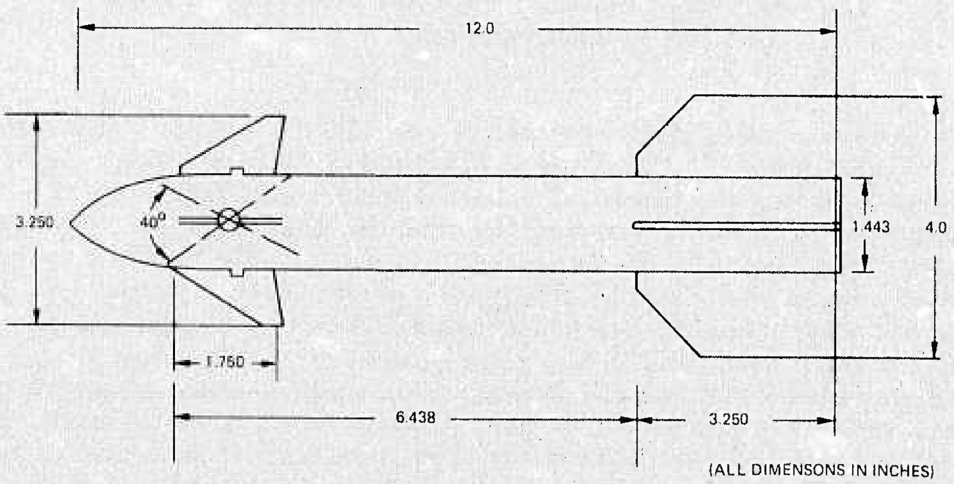


FIGURE 28. Sketch of Free Rolling Model With Commutating Canards.

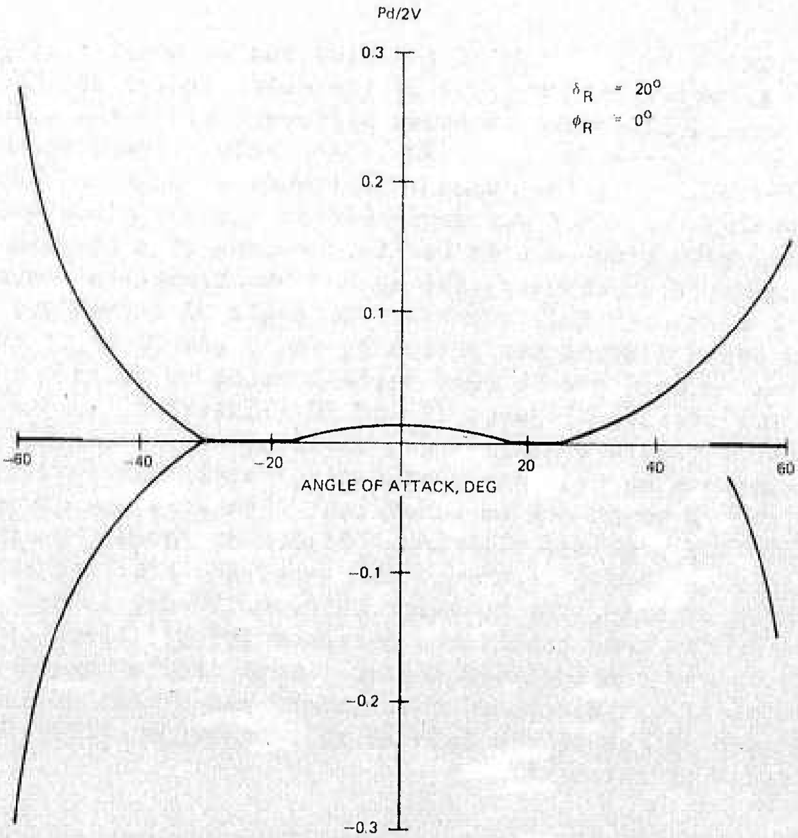


FIGURE 29. Steady-State Roll Rate Versus Angle of Attack for Model With Commutating Canards.

However, when the body-canard was tested without tails, the results shown in Figures 32 and 33 were obtained. With no slots, considerable roll motion was observed. The use of even small slots in the canards eliminated or greatly reduced the rolling motion. Thus, it appeared that if the canard-tail interaction in roll could be eliminated, the use of canard slots would alleviate induced roll moments. To investigate this hypothesis, the model was modified so that a free-to-spin tail, a ring tail, and a flare tail could be incorporated. In general, both the ring tail and flare tail exhibited the same behavior as no tail; i.e., canards slots could be used to suppress the roll rate. The free-to-spin tail did not produce the same results; in all cases, after a brief transient period, the model would begin to roll as a rigid body. The cause of this unexpected result is not definitely known. Possibly the friction between the tail and body was too large, despite the use of low-friction ball bearings. Possibly, the reasons will be discovered during further tests undertaken by Naval Surface Weapons Center (NSWC), White Oak Laboratory, under other funding.

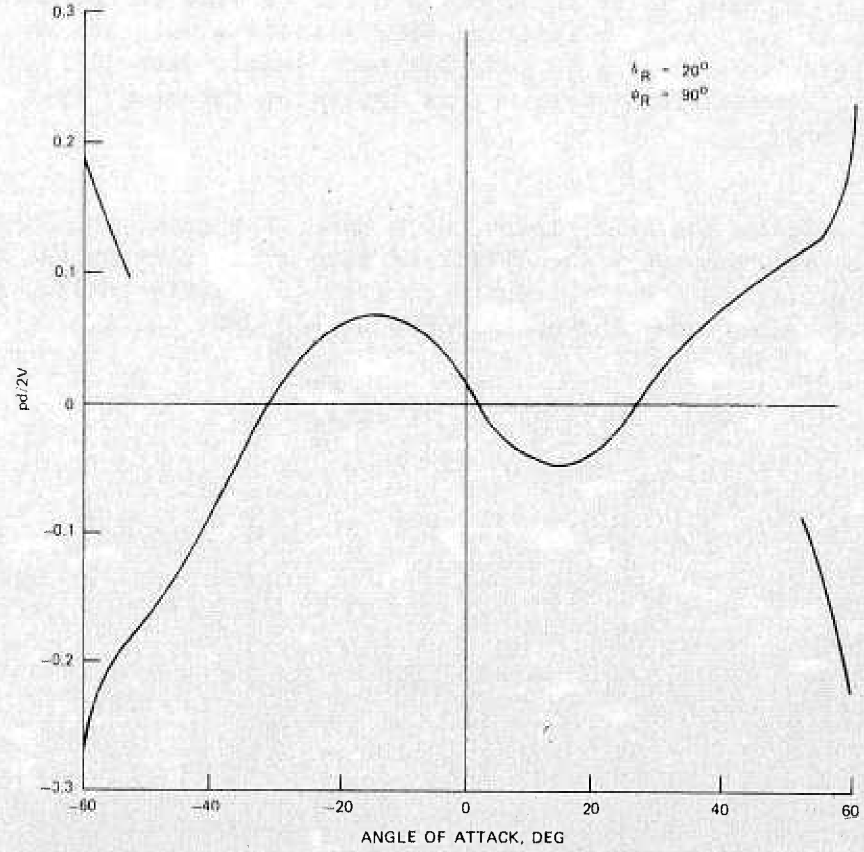


FIGURE 30. Steady-State Roll Rate Versus Angle of Attack for Model With Commutating Canards.

FUTURE PLANS

Although this report represents the end of the Direct Laboratory Funding (DLF) effort, it was felt to be appropriate to discuss briefly the follow-on work growing out of the DLF-supported program.

The method for predicting induced roll moments of canard-controlled missiles has been checked against data to a very limited extent. It is planned to continue this effort under NAVAIR-320 funding. It is planned to also attempt to streamline the computational aspects of the method so as to be better suited as a preliminary design tool.

Also planned is to incorporate a set of wind tunnel data, in phase angle notation, into an existing 6DOF missile simulation and to assess the utility of the PAAS in reducing aerodynamic data storage requirement and computation times, and in improving the accuracy of roll motion predictions.

A program has been planned with NSWC, Dahlgren, and NASA, Ames, to measure experimentally the effect of high roll rates on the aerodynamic roll characteristics of a canard-controlled missile configuration. This effort is also under the sponsorship of AIR-320.

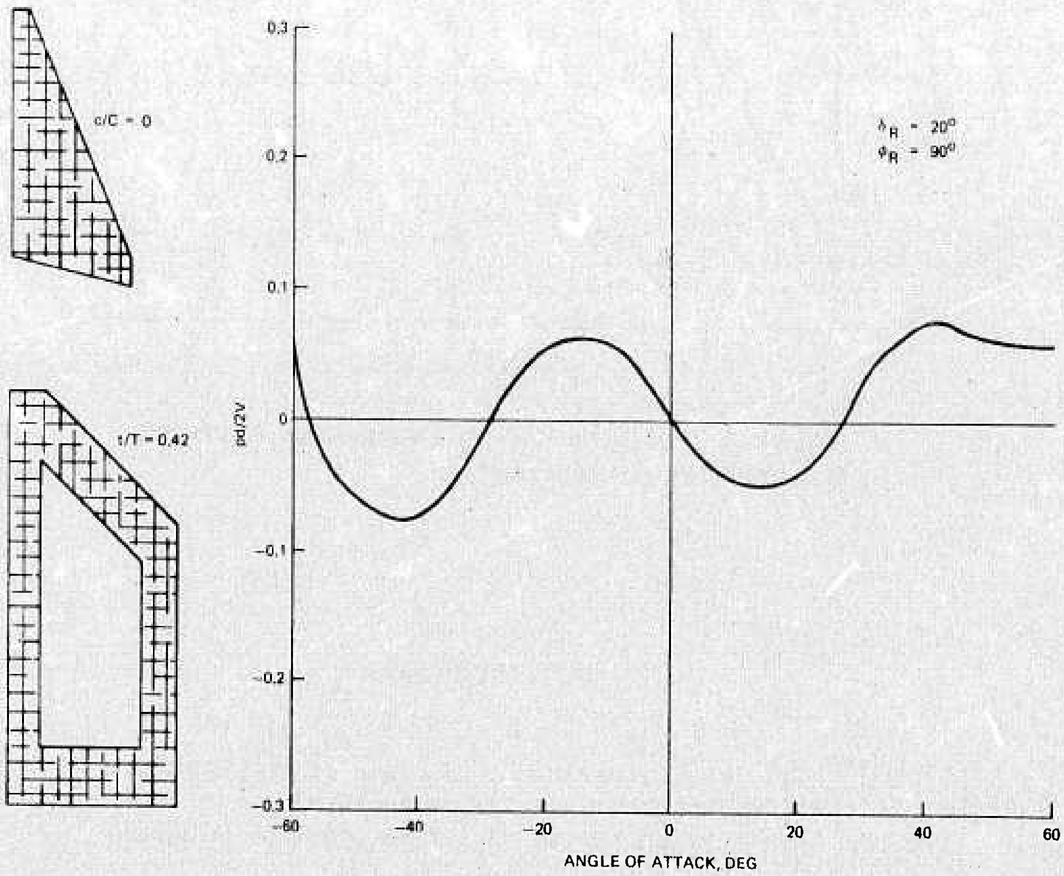


FIGURE 31. Steady-State Roll Rate Versus Angle of Attack for Model With Commutating Canards.

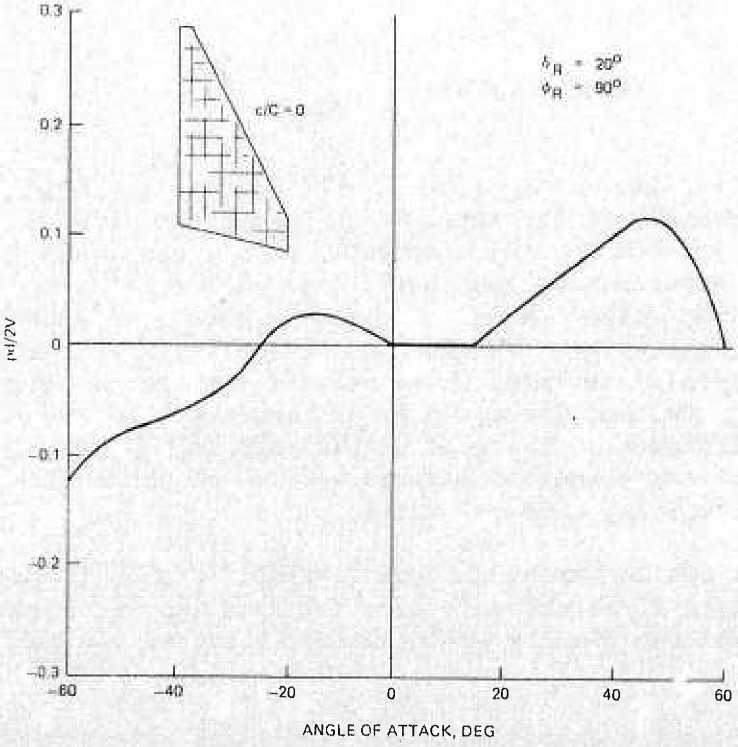


FIGURE 32. Steady-State Roll Rate Versus Angle of Attack for Model With Commutating Canards (c/C = 0 Tail Off).

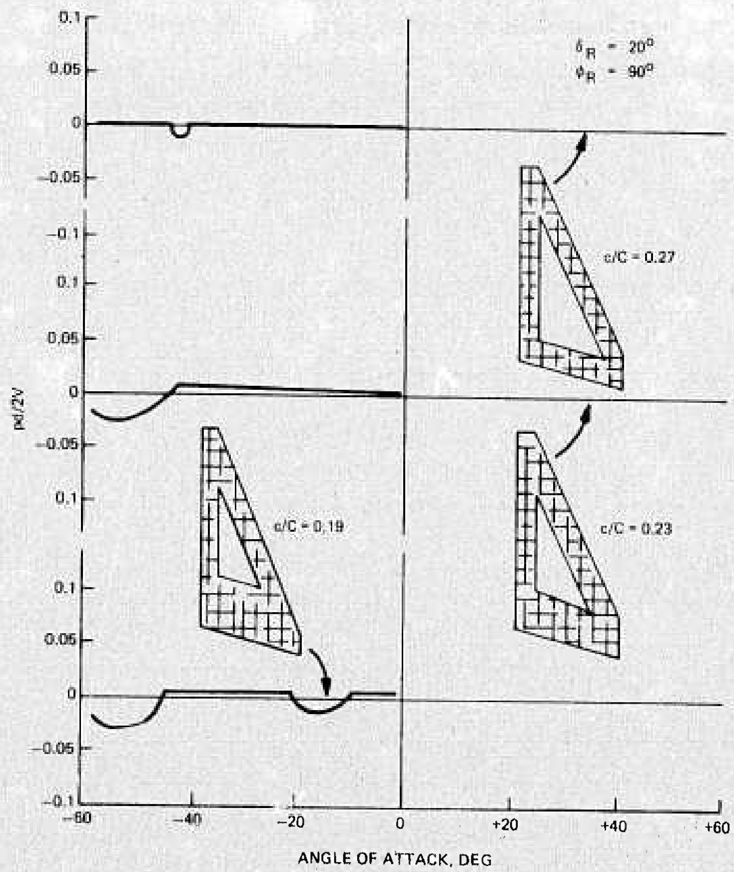


FIGURE 33. Steady-State Roll Rate Versus Angle of Attack for Model With Commutating Canards (Tail Removed, Variable Canard Slot).

CONCLUSIONS

Although the method for predicting induced roll moments has not turned out exactly as expected, it has resulted in unexpected side benefits. First, it has pointed out the complexity of the task, and has indicated where more experimental and theoretical work remains to be accomplished, even if the method should be shown in next year's work to yield good engineering estimates. Second, the method is very general and can account (approximately) for many small effects--effects usually not important in roll moments, but which may be of importance in the calculation of other coefficients. Last, it is the only method around; for the first time, all of the potential effects have been systematically considered and means of computing them put forth.

The phase angle axis system has been shown to yield potential simplifications to the modeling of aerodynamic data for canard-controlled missiles. It is hoped that the results of this simplification can be demonstrated in FY 1976.

The results of the research into canard and tail slots were directly negative. The results did lead through to the observance of other effects which have served as the basis for continuing research by the Naval Surface Weapons Center, White Oak and Dahlgren Laboratories.

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11. Naval Surface Weapons Center. *The Effect of Fin Slots on the Free Rolling Characteristics of a Missile Configuration With Commutating Canard Controls and a Cruciform Stabilizer*, by Peter Daniels. Dahlgren, Va., NSWC. (Report in process.)

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